Working Paper

Trees on farms: an update and reanalysis of agroforestry's global extent and socio-ecological characteristics

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World Agroforestry Centre

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Abstract

Agroforestry, the inclusion of woody perennials within farming systems, has been widespread throughout the tropics as a traditional land use developed by subsistence farmers and, more recently, as an important livelihoods' option promoted by land-use managers and international development agencies. Agroforestry systems range from subsistence livestock and pastoral systems to home gardens, alley intercropping, and biomass plantations with a wide diversity of biophysical conditions and socio-ecological characteristics. A quantification of the extent of agroforestry globally was first attempted by the World Agroforestry Center in 2009 in order to address the widely varying estimates about its importance. Since then, the global remote sensing dataset upon which that estimate was based has been updated, both with improved quality and now including annual datasets available for 11 years (2000–2010). The geospatial analysis of remote sensing-derived global datasets conducted in 2009 investigated the correspondence and relationship of tree cover, population density and climatic conditions within agricultural land at 1 km resolution. This has now been reanalyzed based on the improved data, along with an investigation of change trends from the years 2000 (averaged 2000–2002) to 2010 (averaged 2008–2010). Among the key results are that 1) agroforestry appears to increase globally both in extent and in number of people associated with it; 2) remains a significant feature of agriculture in all regions; 3) that its extent varies significantly across different regions (for example, more widespread in Central America and less in East Asia); 4) that tree cover is strongly positively related to humidity; and that 5) there are mixed relationships between tree cover and population density depending on the region. Agroforestry, if defined by tree cover on agricultural land of greater than 10%, is widespread: found on more that 43% of all agricultural land globally, where 30% of rural populations live. Based on our current analysis, this land-use type represents over 1 billion hectares of land and more than 900 million people. Agroforestry is particularly prevalent in Southeast Asia, Central America, and South America with over 50% of area under agroforestry. Globally, the amount of tree cover on agricultural land increased substantially in the decade under investigation, with the area of >10% tree cover increasing 3%, or more than 828 000 km^2. South America showed the largest increase in area with >10% tree cover: more than 489 000 km^2: an increase of 12.6%. South Asia also showed a large increase (6.7%), along with East Asia (5%), Oceania (3.2%) and Southeast Asia (2.7%). In Central America, the area with >10% tree cover increased by 1.6% to become 96% of all agricultural land. For Sub-Saharan Africa, we found an increase of 2%. Only Northern and Central Asia showed a decrease: - 2.9%. Tree cover apparently is still on the increase as a common feature on agricultural land throughout the world. It is essential that this is recognized by all involved in agricultural production, planning and policy development.

Keywords: land use, spatial modeling, trees, agroforestry, global

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1 Introduction

The inclusion of trees within farming systems, herein referred to as agroforestry, is and has been a traditional land use developed by subsistence farmers throughout almost all of the regions of the world, except where it is too dry or too cold for trees. It is a livelihoods' option often mentioned and increasingly promoted by land-use managers and international development agencies. Over the last 40 years, agroforestry has become a subject for systematic study and improvement, notably with the establishment of the International Centre for Research in Agroforestry (ICRAF) in 1978 (rebranded as the World Agroforestry Centre in 2002). More recently, agroforestry has come to the attention of global analysts and policy makers concerned with environmental sustainability and climate-change adaptation.. (Leakey 2012, Nair and Garrity 2012, FAO 2013), building on earlier policy reports such as NEPAD (2003), Hassan et al. (2005) and UNFCCC (2008).

Removal of trees from landscapes has for long been seen as a sign of intensification and progress, especially where mechanization of agriculture was involved. Agricultural policies in Europe until recently not only assumed that there wouldn't be any trees but made tree-planting experiments illegal. Tree cover on agricultural lands thus has had to catch up with misperceptions and lack of recognition, similar to the 'trees outside forests' as defined by the Food and Agriculture Organization of the United Nations (de Foresta et al 2013) as complements of trees inside forests.

In order to address the widely varying estimates about the prevalence and importance of agroforestry as a land use, a quantification of the extent of agroforestry at the global level was first attempted by the authors using then-available remote sensing datasets, and reported in a working paper published in 2009 (Zomer et al 2009). We used a 1 km^2 resolution, tree-cover data set together with a global land-use layer to investigate the occurrence of agroforestry, which we defined as tree cover on agricultural land when viewed at the scale of data available. We mapped and described the patterns of occurrence in relation to climate and population density. Since then, the global remote sensing dataset upon which that estimate was based (Hansen et al 2005, Collection 3) has been updated (Collection 5), both with an improved resolution (250 m) and higher quality. Further, it now includes annual datasets available for 11 years (2000–2010). Hence we can now reanalyze the global patterns of agroforestry based on the improved data. At the same time, we can now also investigate change trends from the years 2000 (averaged 2000–2002) to 2010 (averaged 2008–2010).

Zomer et al. (2009) was a first attempt to quantify the extent of agroforestry at the global level, and as such, was a work in progress. Several surprising results were reported, not the least of which was the unexpectedly high level of the extent of agroforestry worldwide. Approximately 46% of all agricultural land had at least 10% tree cover. Among the key results were that agroforestry is a significant feature of agriculture in all regions of the world; that its extent varies significantly across different regions (for example, more significant in Central America and less in East Asia); that tree cover is strongly positively related to

humidity; and that there are mixed relationships between tree cover and population density, depending on the region.

Despite this apparent ubiquity and importance, it has been hard to find reliable data on the actual extent of agroforestry around the world (Table 1). This lack of data, and more fundamental misconceptions of what agroforestry is, had led to an assumption that it is globally of little importance. Such misunderstandings lead to suboptimal policy decisions and can best be reversed by providing objective, data-based measures of the extent of agroforestry. Zomer et al (2009) set out with the aim of answering one basic question: How much agroforestry land is there and where is it?

However, agroforestry systems are not easily defined, ranging from subsistence, livestock, silvo-pastoral systems through home gardens, on-farm timber production, tree crops of all types integrated with other crops to biomass plantations, all operating within a wide diversity of biophysical conditions and socio- ecological characteristics. More recently, the term has come to include the role of trees in landscape-level interactions, such as nutrient flows from forest to farm, or community reliance on fuel, timber or biomass available within an agricultural landscape. As such, we set out to understand the extent and distribution of trees on agricultural land at the landscape level, including the numbers and characteristics of farmers and farming communities within those landscapes, in order to assess the importance and role of agroforestry both to the livelihoods of farming communities as well as to global agricultural production. It is our contention that understanding the geographic, ecological and demographic distribution of agroforestry-related land uses highlights those areas where increased tree densities make a greater contribution to livelihoods or landscapes. Based on this premise, once we had a viable analytical method, we realized it would provide much richer data that could answer further questions:

- How many people are associated with agroforestry?
- What patterns can be seen in the density of people on agroforestry land? What patterns of tree cover can be seen across different densities of people?
- How are the patterns of tree cover, population density and their interactions affected by climate and basic ecology?

The updated and higher resolution tree-cover data used in this current analysis, with its higher quality and improved accuracy, allows us to further refine and improve the estimate of the extent of agroforestry based on our previous methodology. In addition, this dataset now has 11 years of data so that we are able to analyze the trends, magnitude and direction of changes in the extent and coverage of tree cover on agricultural land over the recent decade.

2 Measuring the extent of agroforestry

In the current analysis, we adopt the same definition for agroforestry and the same general analytical approach used by Zomer et al (2009). As described in the earlier ICRAF Working Paper, for many years the term ‘agroforestry’ was applied to particular arrangements of trees in crop and animal production systems. This view was summarised as follows.

> Agroforestry is a collective name for land-use systems and technologies, where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components.
>
> ICRAF 1993

Based on this view, several authors have produced estimates of the extent of particular systems, summarized in Zomer et al (2009). In that paper, we also discussed the problem of describing agroforestry as a series of technologies and associated attempts to estimate its extent.

The current view of agroforestry, used in this and our previous analysis, is not as a collection of technologies but of trees included in agricultural landscapes. For example, Schroth and Sinclair (2003) note that agroforestry is increasingly recognized for its ecological and economic interactions at the landscape scale.

This changes the measurement problem considerably, for we have global databases that can be combined and interpreted to generate relevant information. Three data sources were used.

- Global land use. Spatial data layers exist which classify any pixel as agricultural or some other land use.
- Global tree cover. Remotely sensed data has been interpreted to give estimates of the percentage of tree cover in a pixel.
- Global population. Spatially disaggregated population layers are available which give an estimate of population in any pixel and can be used to measure the extent of agroforestry in terms of population.

Details of the data sources are given in the Methods section and further described in Zomer et al (2009). ‘Landscape scale’ is not precisely defined. However, each of the above data sources is available, at least, at a minimum resolution of 1 km x 1 km resolution. This corresponds roughly to a common notion of ‘landscape scale’. Thus, we looked at the 1 km x 1 km grid cells that are classified as ‘agriculture’ and found the percentage of tree cover in each. This varied from 0%—clearly not agroforestry—up to close to 100%, though most pixels with high tree cover have not been classified as agricultural. It is not necessary to choose a cut-off value for tree cover below which we do not consider the landscape as being an agroforestry landscape. Most results can be presented as a continuum of patterns from low-to-high tree cover, a continuum which represents reality better than any arbitrary cut off.

We can then assume the population estimated as living in the 1 km x 1 km pixel is in some sense ‘connected with’ that agricultural landscape and its trees. While we do not know the

extent to which those people depend on the agroforestry landscape, it is reasonable to assume that at the 1 km scale they are influenced by, and influence, that landscape.

The limitations of this approach are numerous, with the major ones being outlined in the Discussion and previously discussed in Zomer et al (2009). However, we believe it has been a step forward compared with other estimates to date, particularly when it is understood as a global assessment, and that the current analysis significantly improves and refines our estimates and understanding. We do not expect the results of every grid cell to closely match an observation on the ground but expect the broad patterns to be revealing.

The changes over the period from 2000 to 2010 described in this analysis are changes in tree cover only. We have used a land-cover layer from 2000, that is, the same used in the previous Zomer et al (2009) analysis. Thus, we can describe the changes in tree cover on land classified as agricultural in 2000. There may be additional changes owing to land becoming, or stopping being, agricultural during that time.

3 Methods

3.1 Geodatasets

The global geospatial analysis in Zomer et al (2009) combined tree cover, with land-use classification, population density (disaggregated by a delineation of rural extent) and an aridity index. In this current analysis, we have used all the same basic datasets, with the exception of the now-updated and multi-year (that is, 11 years) tree-cover data, described in detail below. We did this partly to maintain continuity and comparability with the earlier analysis but also because there have been no updates of the previously used global datasets.

The spatial modeling procedure was developed and implemented in ArcGIS 10.2 (ESRI Inc.) using both ArcAML and Python programming language. All datasets used for the analyses have been re-projected into two coordinate systems: sinusoidal and geographic. The sinusoidal projection has been used to calculate zonal statistics and carry out areal computations as it represents area extent accurately across latitudes (that is, equal-area projection). The cell size for analyses in sinusoidal projection is 1 km^2. The datasets in geographic coordinates are used for map presentation purposes.

The geodatasets used in the current analysis are listed below. They are described more fully and mapped in the appendix of Zomer et al (2009).

- VMAP 0: Country Boundaries (NIMA 1997)
- MOD44B MODIS Vegetation Continuous Field Coll. 3–2000: Percent Tree Cover (Hansen et al 2003)
- MOD44B MODIS Vegetation Continuous Field Coll. 5–2000 through to 2010: Percent Tree Cover (DiMiceli et al 2011)
- Global Land Cover 2000 database (GLC 2000)
- Global Rural-Urban Mapping Population (GRUMP v. 1) (CIESIN 2004)
- Aridity Index (Zomer et al 2007) (see below for a relabeling of this index)

3.1.1 Land-cover categories

Three agricultural land-use types from the Global Land Cover Class scheme used for the Global Land Cover 2000 database were selected as relevant for the specific objectives of this work: *Cultivated and managed areas* (Agriculture — intensive), *Cropland/Other natural vegetation* (non-trees) (Mosaic agriculture/degraded vegetation) and *Cropland/Tree Cover Mosaic* (agriculture/degraded forest).

Although at first the Cropland/Tree Cover Mosaic type seems to identify agroforestry systems, we noted that the mix of forest and agriculture does not occur at discrete intervals but is a gradient where the two components of landscape-level agroforestry mix within the landscape. The mix of tree cover over agriculture land is depicted along a continuous gradient by the MODIS VCF tree-cover dataset, within the relevant GLC2000 land-cover type. Tree cover shows the percentage of the 1 km^2 grid cell occupied by trees, therefore, at this resolution of 1000 m, the tree-cover percentage can be expressed as hectares (ha) of tree cover per km^2. At 100% tree cover, the whole grid cell is occupied, that is, 100 ha/km^2.

3.1.2 Aridity–Wetness Index

A global model of aridity (Zomer et al 2006, 2007) was used to stratify ecological conditions based on climatic and agro-ecological characteristics. Aridity is expressed as a function of precipitation, temperature and potential evapotranspiration (*PET)*. Based upon an attempt to classify climatic zones by moisture regime, the Aridity–Wetness Index (*AWI*) quantifies precipitation deficit over atmospheric water demand as:

Aridity–Wetness Index (*AWI*) = *MAP* / *MAE* [1]

where:

MAP = mean annual precipitation

MAE = mean annual evapotranspiration

3.1.3 Tree-cover data

The MOD44B MODIS/Terra Vegetation Continuous Fields Dataset (VCF) – Collection 3 (Hansen 2003) was developed by the University of Maryland and provides global estimates of vegetation cover in terms of woody vegetation, herbaceous vegetation and bare-ground percentages. It was developed using the 7 MODIS bands with highest resolution (500 m) and field data collected across the globe as training data. The training data and phenological metrics were used with a regression method (and some human intervention) to derive the global assessment of tree-cover percentage. Quantifications of the accuracy of the MODIS VCF (Hansen et al 2003) and other continuous-field datasets (for example, Homer et al 2004, Asner et al 2009, Rollins 2009, Hansen et al 2011) have been scarce but indicate that the MODIS VCF dataset tends to overestimate tree cover in sparsely treed areas and underestimate cover in dense forests (Sexton et al 2013). The latter is likely due to the saturation of the MODIS VCF tree-cover estimates at approximately 80% cover and the former is likely due to poor discrimination between trees and dense herbaceous vegetation.

The updated MOD44B MODIS VCF – Collection 5 dataset used in the current analysis improves upon this methodology and provides data at the higher resolution of 250 m. Improved training data and the implementation of new and improved data mining software have resulted in much greater accuracy in the final product without human intervention (see User Guide for VCF Collection 5 – Version 1). Overall the output is substantially better than the previous 500 m version in spatial detail and coherence. A limited amount of validation performed using field data from two sites in Maryland and three sites in Brazil, South America (see User Guide for VCF Collection 5 – Version 1) show that the new Collection 5VCF product is substantially more accurate compared to ground-based measurements of canopy cover with as much as a 50% improvement in RMSE between the two versions. Notably, accuracy was significantly improved within agricultural areas and forest clearings.

3.2 Processing and presenting results

In the case of the VCF Tree Cover – Collection 5 dataset used in the current analysis, the 250 m resolution grid cells were aggregated to 1 km resolution, as was done in the previous analysis with the Collection 3 dataset. All the geodatasets have been masked to exclude areas which are either non-agricultural land-use types or urban areas. Successively, the agricultural land extent has been stratified for each tree-canopy cover value (0 to 100), by population density, aridity index and subcontinents (North America, Central America, South America, Europe, North Africa, West and Central Africa, Eastern and Southern Africa, Western Asia, Northern and Central Asia, South Asia, East Asia, Southeast Asia, Australian Area). Within each stratum, or within specific aggregation of strata, zonal statistical values (mean, sum, total area, percentiles, areal distribution etc) were summarized to describe those factors of interest for this study: tree-canopy cover (percentage), total population and population density. Only results from developing countries are highlighted in this report, although the analysis is complete for the total global extent of the datasets, and tables contain results from all regions.

Cumulative agricultural area and cumulative population is presented at decreasing tree-canopy cover to infer at global and subcontinent scales the total population and area engaged above any specific tree-canopy cover values. In a second stage, the same cumulative distribution of population and total agricultural land in function of tree-canopy cover has been disaggregated for five different aridity classes ($AI < 0.45$ or arid, $0.45 < AI < 0.6$ or semi-arid, $0.6 < AI < 0.8$ or sub-humid, $0.8 < AI < 1.0$ or humid, $AI > 1.0$ or very humid) to show how climate regimes might differentiate specific patterns of interdependence between tree-canopy cover with population pressure (total population and average population density) and land surface available for different geographical areas.

4 Results

The characteristics, assumptions and limitations of the data layers and methods condition all the results. These are discussed in Section 5. The results should not be used or quoted without understanding these limitations.

We focus on two aspects of the results here. The first is an update to the results of Zomer et al (2009) of the global patterns on agroforestry in 2000 owing to the improved tree-cover layer. The second is the description of changes in tree cover from 2000 to 2010 as detected with the currently available dataset.

4.1 Updated estimates of the extent of agroforestry in the year 2000

4.1.1 Comparison of the tree-canopy cover on agricultural land in the year 2000 between VCF Collection 3 and Collection 5

The difference in tree-cover percentage between the updated VCF Collection 5 (VCF-C5) and the VCF Collection 3 (VCF-C3) dataset used previously is mapped in Figure 1. There is a strong coherence in the patterns of difference between the two estimates. For example, there are large reductions in estimates of tree cover on agricultural land particularly evident from West Africa, Tanzania, parts of Ethiopia, Brazil and Nepal. The new estimates of tree cover tend to be higher in China, northwestern India, parts of Argentina, and the eastern coast of Mexico.

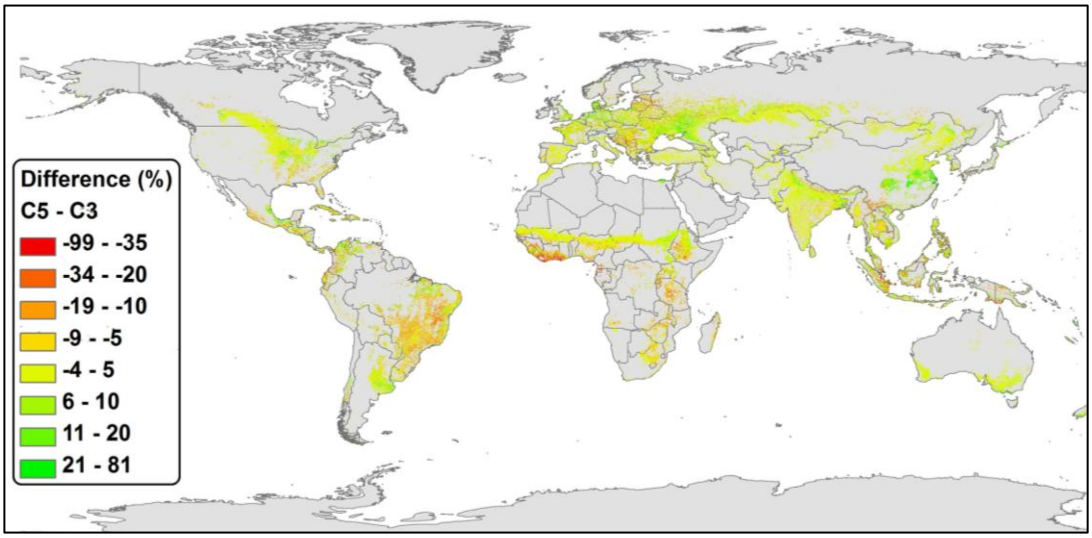


Figure 1. Percentage of tree cover in the year 2000, showing the difference (C5 minus C3) between two datasets for the same year: Collection 5 and Collection 3

A comparison of the amount of agricultural land with greater than 10%, 20% and 30% tree cover in the year 2000 (tables 1 and 2) shows significant differences between the earlier analysis based on VCF-C3 and the current analysis using the updated VCF-C5. The percentage of agricultural land with greater than 10% tree cover globally is reduced from 46% in the VCF-C3 to 40% in the VCF-C5, amounting to a reduction of more than 1.1

million km^2. Similar substantial reductions occur in the VCF-C5 for greater than 20% (27% or 6% less than C3) and greater than 30% (17% or 4% less). Nevertheless, these still continue to represent substantial areas of agricultural land with significant tree cover (more than 10.1 million km^2 with greater than 10% tree cover). Likewise, substantial reductions in the estimates of agricultural land with tree cover are seen in South America (from 81% to 52 %), Sub-Saharan Africa (from 47% to 27%), Southeast Asia (from 82% to 77%) and Central America (from 98% to 92%). On the other hand, we see increases in the revised estimates for 2000 using the VCF-C5 for East Asia (from 23% to 45%), Northern and Central Asia (from 27% to 35%), and Oceania (from 24% to 29%).

Table 1. Comparison of the amount of agricultural land in the year 2000 (km^2) with greater than 10%, 20%, 30% tree cover, showing the difference between the previous report (Collection 3) and the current data (Collection 5)

Tree cover	>10%		>20%		>30%		Agriculture (>0%)	
	Collection 3	Collection 5	Collection 3	Collection 5	Collection 3	Collection 5	Collection 3	Collection 5
Region								
North America	800,632	838,372	528,745	513,481	346,194	311,648	2,073,358	2,073,352
Central America	265,057	247,708	217,731	188,092	140,165	134,218	269,503	269,503
South America	3,159,991	2,018,713	1,726,431	1,141,032	887,714	704,487	3,888,964	3,888,963
Europe	914,122	1,135,205	529,438	471,390	354,654	245,291	2,301,065	2,301,062
North Africa / Western Asia	105,298	117,000	58,598	59,830	38,956	34,504	1,138,842	1,138,842
Sub-Saharan Africa	1,875,543	1,089,278	974,333	528,602	595,834	345,302	3,964,974	3,964,972
Northern and Central Asia	657,008	866,020	299,563	235,548	160,946	89,286	2,473,698	2,473,698
South Asia	389,056	341,064	161,463	122,070	97,160	70,837	1,828,928	1,828,926
Southeast Asia	1,346,888	1,266,843	1,059,471	980,562	826,577	768,476	1,652,548	1,652,548
East Asia	417,273	803,968	273,466	365,767	188,122	167,104	1,800,449	1,800,443
Oceania	190,466	230,185	128,487	150,724	108,202	110,471	790,875	790,875
Global Total	**10,121,334**	**8,954,356**	**5,957,726**	**4,757,098**	**3,744,514**	**2,981,624**	**22,183,204**	**22,183,184**

Table 2. Comparison of the percentage of agricultural land in the year 2000 with greater than 10%, 20%, 30% tree cover, showing the difference between the previous report (Collection 3) and the current data (Collection 5)

Tree cover	>10%		>20%		>30%	
	Collection 3	Collection 5	Collection 3	Collection 5	Collection 3	Collection 5
Region						
North America	39	40	26	25	17	15
Central America	98	92	81	70	52	50
South America	81	52	44	29	23	18
Europe	40	49	23	20	15	11
North Africa/Western Asia	9	10	5	5	3	3
Sub-Saharan Africa	47	27	25	13	15	9
Northern and Central Asia	27	35	12	10	7	4
South Asia	21	19	9	7	5	4
Southeast Asia	82	77	64	59	50	47
East Asia	23	45	15	20	10	9
Oceania	24	29	16	19	14	14
Global total	**46**	**40**	**27**	**21**	**17**	**13**

4.1.2. Updated estimates of tree-canopy cover on agricultural land in the year 2000 (2000–2002 averaged) based on VCF Collection 5

Tree-canopy cover on agricultural land has been tabulated for all years available in the VCF-C5 dataset, that is, from 2000 to 2010 (Table 3). Variation in the estimates from year to year appears to be high and not consistent with the expected year-to-year change. There is a fair amount of ‘noise’ in the year-to-year estimates, which can be expected from having a significant coefficient of variation associated with the quality of the remote-sensing dataset and seasonal and other confounding factors affecting the classification algorithm used in the VCF-C5 processing. In order to reduce the effect of this variability in estimates of change during the period, we have averaged the first three years of the dataset (2000–2002) and the last three years (2008–2010) and use these averaged results as the beginning and end points for the change analysis. A comparison of the results when examining the difference between the years 2000 and 2010, and when using the averaged results, shows minor but significant differences in the results obtained (tables 4 and 5). Based on this result, we use the averaged results for the years 2000–2002 and 2008–2010 for all the VCF-C5 estimates presented in this analysis and compare the VCF-C5 2000–2002 averages to the 2000 VCF-C3 estimates in Zomer et al (2009).

Table 3. Percentage of tree cover on agricultural land based on VCF-Collection 5, showing yearly averages for each year from 2000 to 2010

Sub-continent	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Difference 2010–2000
North America	13.8	13.9	13.7	13.8	14.2	13.9	13.9	14.3	14.5	14.7	13.9	0.1
Central America	33.1	32.0	32.4	32.9	31.6	31.6	35.6	36.2	34.2	34.2	34.6	1.5
South America	17.7	17.2	18.1	17.1	18.3	18.3	19.0	18.5	18.7	18.7	19.9	2.2
Europe	14.2	14.2	13.5	12.5	14.4	14.1	14.7	14.9	14.7	14.7	14.5	0.3
North Africa/Western Asia	4.4	4.4	4.8	4.7	4.6	4.7	4.9	5.0	4.8	4.8	5.3	1.0
Sub-Saharan Africa	10.6	11.0	11.8	11.6	10.6	11.1	12.0	11.4	11.2	11.2	10.5	-0.1
Northern and Central Asia	10.0	9.2	8.6	10.2	9.7	8.8	10.4	10.0	9.6	9.6	7.9	-2.1
South Asia	7.6	84	8.7	8.2	9.0	9.5	10.0	9.0	9.4	9.4	9.5	1.9
Southeast Asia	31.2	30.9	31.8	31.1	30.8	32.2	31.9	33.1	32.5	32.5	34.0	2.9
East Asia	13.3	12.5	13.1	13.3	13.5	13.3	13.1	14.6	14.5	14.5	15.0	1.7
Oceania	13.0	14.0	12.8	14.3	13.4	13.9	14.3	13.6	14.5	14.5	15.1	2.1
Global	**14.0**	**13.9**	**14.2**	**14.0**	**14.2**	**14.4**	**14.9**	**14.8**	**14.8**	**14.7**	**14.8**	**0.8**

Table 4. Amount of agricultural land (km^2) with greater than 10%, 20%, 30% tree cover—A) based on single-year data for the years 2000 and 2010; B) using 3-year averages (2000–2002 and 2008–2010)—for the early and late part of the decade

Tree cover	>10%		>20%		>30%		Agriculture (>0%)
A. Single year	**2000**	**2010**	**2000**	**2010**	**2000**	**2010**	
North America	838,372	859,744	513,481	509,672	311,648	302,460	2,073,358
Central America	247,708	253,396	188,092	201,846	134,218	142,667	269,503
South America	2,018,713	2,597,784	1,141,032	1,294,088	704,487	750,424	3,888,964
Europe	1,135,205	1,099,076	471,390	492,165	245,291	279,633	2,301,065
North Africa/ Western Asia	117,000	128,980	59,830	66,818	34,504	41,388	1,138,842
Sub-Saharan Africa	1,089,278	1,137,864	528,602	582,064	345,302	353,961	3,964,974
Northern and Central Asia	866,020	584,828	235,548	212,692	89,286	90,460	2,473,698
South Asia	341,064	493,723	122,070	155,832	70,837	76,643	1,828,928
South-East Asia	1,266,843	1,286,085	980,562	1,029,377	768,476	839,893	1,652,548
East Asia	803,968	908,811	365,767	418,861	167,104	232,268	1,800,449
Oceania	230,185	296,596	150,724	189,649	110,471	130,695	790,875
Global total	**8,954,356**	**9,646,887**	**4,757,098**	**5,153,064**	**2,981,624**	**3,240,492**	**22,183,204**
Increment	692,531		395,966		258,868		
B. Average of 3 years	**2000–2002**	**2008–2010**	**2000–2002**	**2008–2010**	**2000–2002**	**2008–2010**	**2000–2002**
North America	837,230	878,917	498,671	546,175	293,252	322,280	2,073,358
Central America	254,658	259,023	190,669	212,930	127,264	147,669	269,503
South America	2,062,254	2,552,178	1,099,578	1,235,601	654,672	687,135	3,888,964
Europe	1,035,079	1,035,123	431,872	469,704	239,957	267,864	2,301,065
North Africa/ Western Asia	114,966	125,315	59,104	62,732	32,654	37,830	1,138,842
Sub-Saharan Africa	1,134,560	1,207,656	594,054	595,334	356,978	334,492	3,964,974
Northern and Central Asia	697,514	625,933	209,690	239,694	89,164	107,419	2,473,698
South Asia	384,772	507,433	126,421	142,298	68,536	65,746	1,828,928
South-East Asia	1,271,181	1,316,106	1,007,100	1,039,249	785,166	823,783	1,652,548
East Asia	767,415	854,653	337,326	398,606	153,370	211,841	1,800,449
Oceania	237,460	263,066	161,434	188,571	113,918	134,760	790,875
Global total	**8,797,089**	**9,625,303**	**4,715,919**	**5,130,893**	**2,914,931**	**3,140,819**	**22,183,204**
Increment	828,214		414,974		225,888		

Table 5. Percentage of agricultural land with greater than 10%, 20%, 30% tree cover—**A)** based on single-year data for the years 2000 and 2010; **B)** using 3-year averages (2000–2002 and 2008–2010)—for the early and late part of the decade

1. Tree cover	**>10%**		**>20%**		**>30%**	
A. Single year	**2000**	**2010**	**2000**	**2010**	**2000**	**2010**
North America	40.4	41.5	24.8	24.6	15.0	14.6
Central America	91.9	94.0	69.8	74.9	49.8	52.9
South America	51.9	66.8	29.3	33.3	18.1	193
Europe	49.3	47.8	20.5	21.4	10.7	12.2
North Africa / Western Asia	10.3	11.3	5.3	5.9	3.0	3.6
Sub-Saharan Africa	27.5	28.7	13.3	14.7	8.7	8.9
Northern and Central Asia	35.0	23.6	9.5	8.6	3.6	3.7
South Asia	18.7	27.0	6.7	8.5	3.9	4.2
Southeast Asia	76.7	77.8	59.3	62.3	46.5	50.8
East Asia	44.7	50.5	20.3	23.3	9.3	12.9
Oceania	29.1	37.5	19.1	24.0	14.0	16.5
Global	**40.4**	**43.5**	**21.4**	**23.2**	**13.4**	**14.6**
Increment	3.1		1.8		1.2	
B. Average of 3 years	**2000-2002**	**2008-2010**	**2000-2002**	**2008-2010**	**2000-2002**	**2008-2010**
North America	40.4	42.4	24.1	26.3	14.1	15.5
Central America	94.5	96.1	70.8	79.0	47.2	54.8
South America	53.0	65.6	28.3	31.8	16.8	17.7
Europe	45.0	45.0	18.8	20.4	10.4	11.6
North Africa / Western Asia	10.1	11.0	5.2	5.5	2.9	3.3
Sub-Saharan Africa	28.6	30.5	15.0	15.0	9.0	8.4
Northern and Central Asia	28.2	25.3	8.5	9.7	3.6	4.3
South Asia	21.0	27.7	6.9	7.8	3.8	3.6
Southeast Asia	76.9	79.6	60.9	62.9	47.5	49.9
East Asia	42.6	47.5	18.7	22.1	8.5	11.8
Oceania	30.3	33.3	20.4	23.8	14.4	17.0
Global	**39.7**	**43.4**	**21.3**	**23.1**	**13.1**	**14.2**
Increment	3.7		1.8		1.1	

Tree-canopy cover on agricultural land has been mapped at the global level for the years 2000–2002, shown in Figure 2a. Tree cover varies from 0% to 85%. However, in the updated analysis (Figure 2b), only about 5% (Figure 3, right-hand axis) of land classified as agricultural has more than 50% tree cover (reduced from 7% in the previous analysis).

As in the previous analysis, the global variation continues to broadly follow climatic zones, with high tree cover (>45%) found in the more humid regions, such as Southeast Asia,

Central America, eastern South America and coastal West Africa. Moderate levels of 10% to 30% cover describe the majority of agricultural areas in South Asia, Sub-humid Africa, Central and Western Europe, Amazonian South America, and Mid-western North America.

At the other extreme are agricultural areas with relatively low (<10%) tree cover, such as eastern China, northwestern India and the Punjab, West Asia, the southern border of the Sahara, the northern prairies of North America and the southwest of Australia. As seen earlier, tree-canopy cover follows a pattern influenced by precipitation regimes. As before, specific divergences of tree-canopy cover from climate influence are stronger where population density or human activities are higher (for example, China, India).

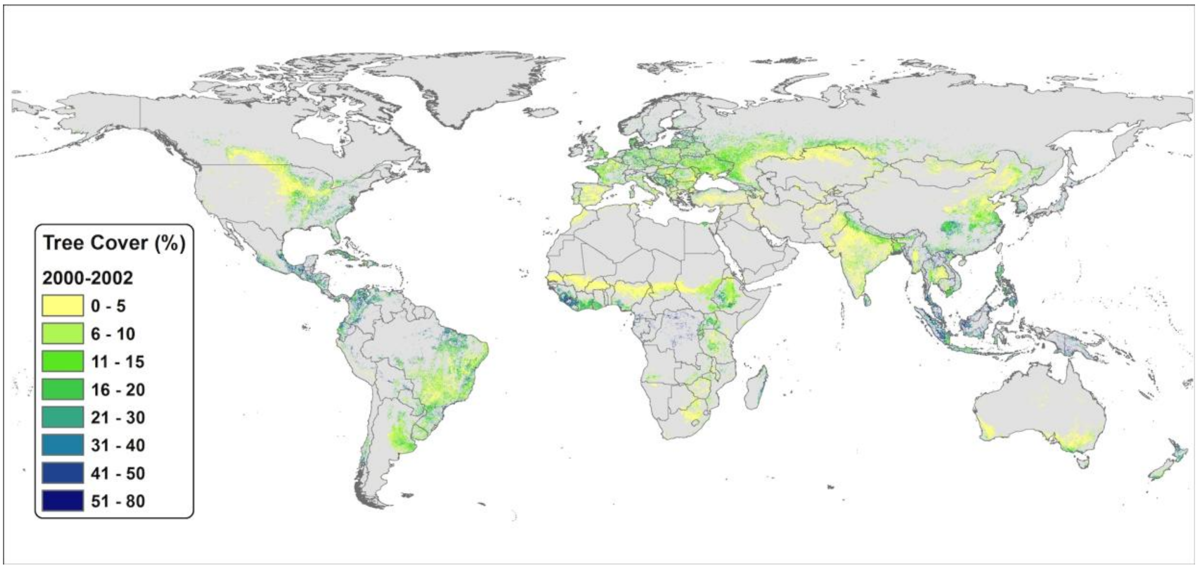


Figure 2a. Global percentage of tree cover in the year 2000–2002 (averaged)

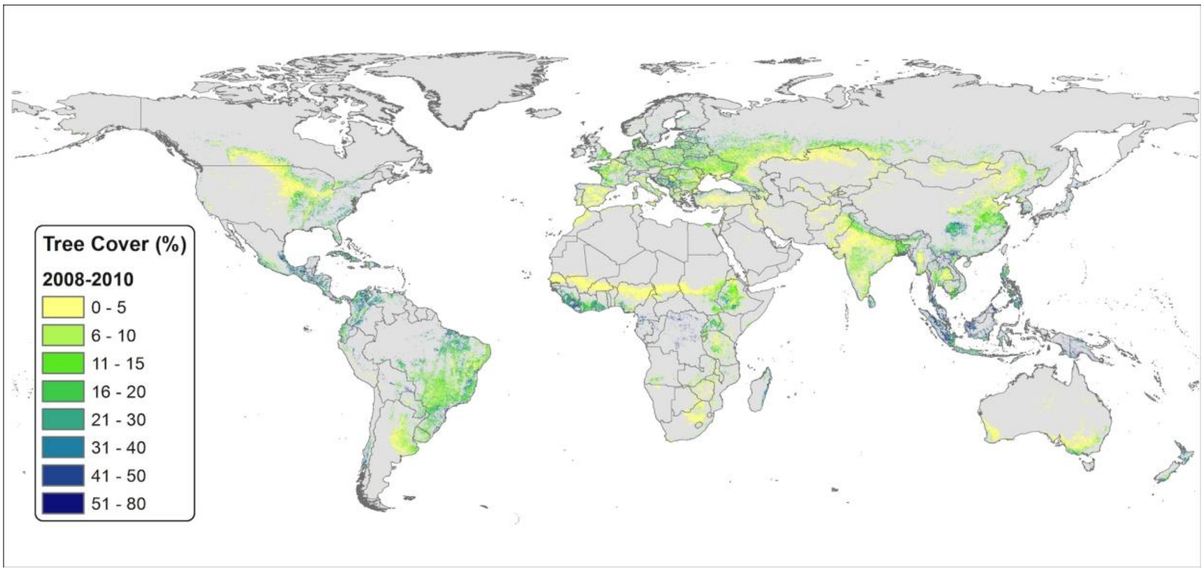


Figure 2b. Global percentage of tree cover in the years 2008–2010 (averaged)

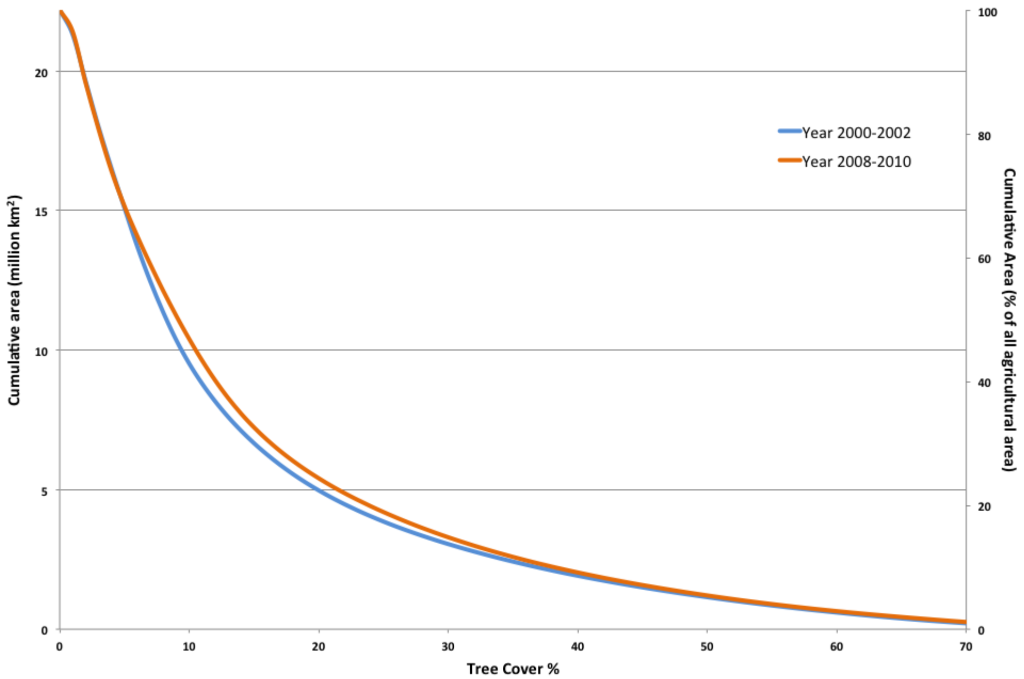


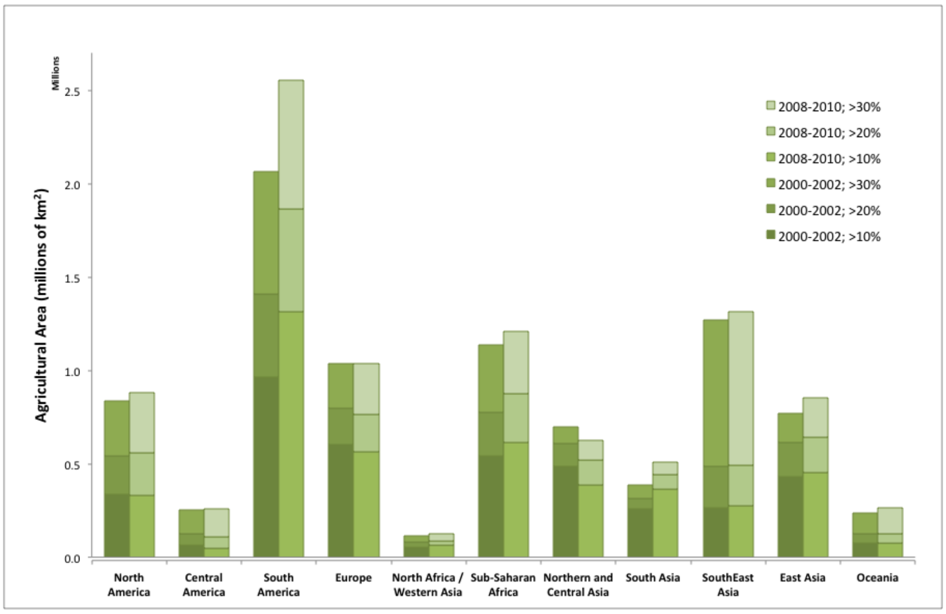
Figure 3. Cumulative area (km^2) versus tree cover, comparing average of 2000–2002 and 2008–2010

The total global area classified as agricultural in our database is 22 183 204 km^2. Figure 3 shows the global cumulative agricultural area as tree-canopy cover decreases. Thus, 8 797 089 km^2 (40% of agricultural land) have more than 10% tree cover; 4 715 919 km^2 (22% of agricultural land) have more than 20% tree cover; and only 1 211 265 km^2 (5%) have more than 50% tree cover. As stated earlier, it is not helpful to label some minimum tree-cover percentage as representing ‘agroforestry’, as the reality is a continuum of tree-cover fractions from zero to high. The way trees are integrated into the farming landscape and used in agriculture varies across the world and there are prominent and economically important agroforestry systems which nonetheless have low tree-canopy cover in landscapes. Examples are the parkland systems in the Sahel and the poplar–wheat/barley agroforestry systems of northern India.

However, for the purpose of presenting numerical tables, we show results for 10%, 20% and 30% tree cover. Figure 4 shows in graphical form the agricultural areas under tree cover in each major region. The numbers presented are cumulative such that, for example, the area under tree cover of greater than 20% is inclusive of the area shown under tree cover of greater than 30%. The percentage of land under each level of tree cover is also given, calculated using the total agricultural land area in the last column.

Globally, a (revised) cautious estimate of agricultural land that involves agroforestry for the year 2000 (that is, 2000–2002) is 13% (>30% tree cover), with a more realistic one being about 40% (>10% tree cover). Using our definition of agricultural land (covering 22.2 million km^2) and a 10% tree-cover threshold for agroforestry, there were slightly less than 9 million km^2 of agricultural land in the years 2000–2002 which were also under agroforestry. Large areas of agroforestry are found in South America (2.1 million km^2), in Sub-Saharan Africa (1.1 million km^2) and Southeast Asia (1.3 million km^2). Europe and North America also have

significant absolute areas of agroforestry, despite having large commercial agricultural sectors.



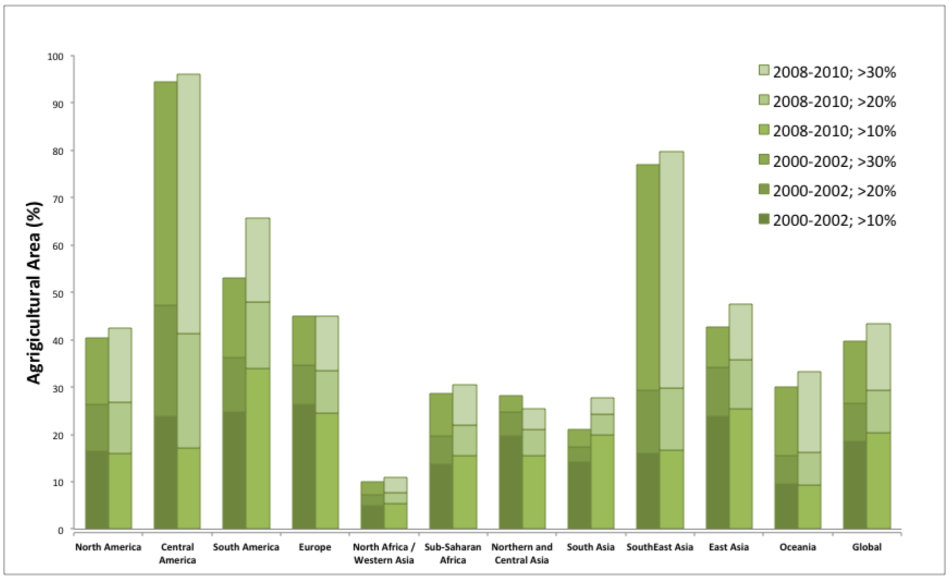


Figure 4. Amount of agricultural land (km^2 and %) with greater than 10%, 20%, 30% tree cover, showing the difference when using the average of 2000–2002 and 2008–2010

Trees are an integral part of the agricultural landscape in *all* regions except North Africa/West Asia. Much of Central America's agriculture (95%) has >10% tree cover, as does 77% of Southeast Asian agriculture (revised downward from 81%), Estimates for South American agriculture have been revised significantly downward from 81% to 53%, as have estimates for Sub-Saharan Africa (from 47 to 27%). Significant proportions of land under agroforestry are found in Europe (revised upward from 40% to 49%), North America (40%) and East Asia (revised upward from 23% to 45%), with all the remaining regions apart from

North and West Africa (10%) and South Asia (19%) showing at least 27% of agricultural land under agroforestry.

The percentage of agricultural land with substantial tree cover (>30%) continues to be remarkably high in some regions: over 47% in Central America and Southeast Asia. In these areas, which have substantial cover of tree crops and ‘agroforests’ (probably often omitted from agricultural land analysis), the wider agricultural landscapes are also well stocked with trees. In all regions, however, the contribution of high tree-cover agroforestry (>30%) to total agroforestry (>10%) is significant; the lowest being in South Asia where the proportion is 14%. Nonetheless, the prominence of sparser tree cover (between 10% and 20% tree cover) in relation to tree cover greater than 20% is high in some regions, such as South America, Sub-Saharan Africa, Northern and Central Asia, South Asia and Europe.

4.2 Estimates of tree-canopy cover change on agricultural land from 2000–2002 (averaged) to the years 2008–2010 (averaged) based on VCF Collection 5

The global tree cover on agricultural land for the years 2008–2010 is shown in Figure 2b above, while Figure 5 (below) provides a map of the changes from 2000–2002 to 2008–2010. Globally, the amount of tree cover on agricultural land increased substantially, with the area >10% increasing by more than 828 000 km^2 (from 40% to 43% of all agricultural land), the area >20% increasing by more than 414 000 km^2 (from 21% to 23%) and that with >30% by more than 225 000 km^2 (from 13% to 14%). South America showed the largest increase in area with >10%—more than 489 000 km^2—an increase of 12.6% of all agricultural land. South Asia also showed a large increase (6.7%), along with East Asia (4.85%), Oceania (3.2%), Southeast Asia (2.7%) and North America (2%). Central America, which increased 1.6% to 96% of all agricultural land having greater than >10% tree cover, showed a large increase in area >20% (8.2%) and >30% (7.6%), indicating, perhaps, an increase in canopy density on agroforested land owing to maturing trees. Sub-Saharan Africa, which showed an increase of 1.85% of land with >10% tree cover, however, also showed a small decrease (-0.56%) of land with >30%. Only Northern and Central Asia showed a decrease of agricultural land with >10% (- 2.9%).

Remember that these changes are only estimates of changed tree cover on the same land units. The analysis does not account for any change in the land-use classifications during the period studied. It is likely that, in addition to change in tree cover, there has been a change in land units (or 1 km^2 pixels) that should be classified as agricultural.

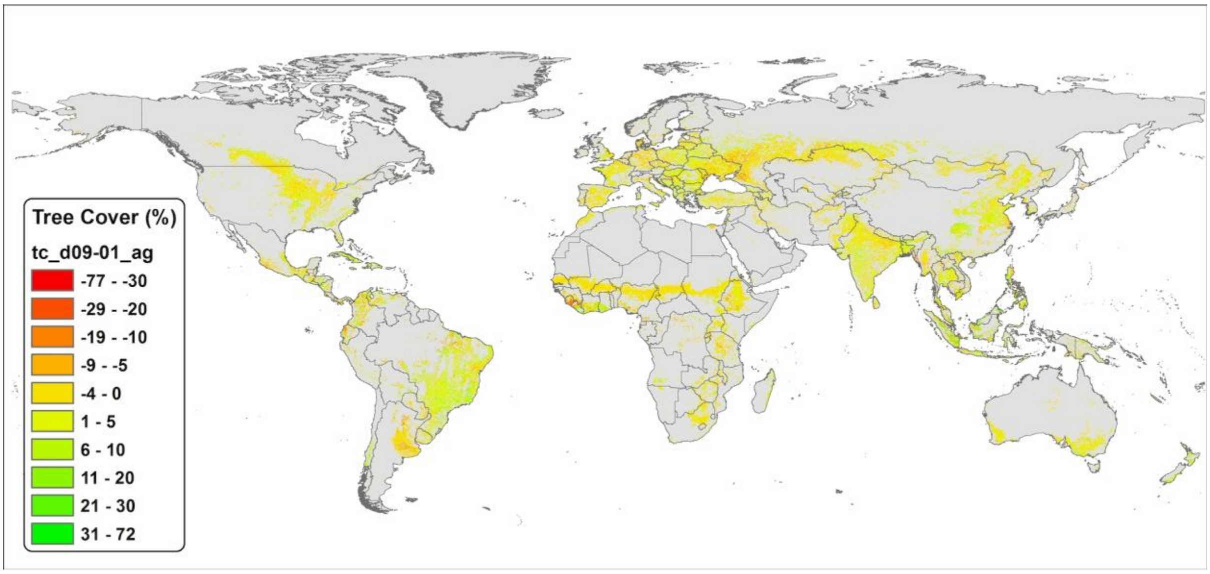


Figure 5. Change in global percentage of tree cover from the years 2000–2002 (averaged) to the years 2008–2010 (averaged)

4.3 Estimates of the extent of and change in agroforestry by population

The analysis of the area under agroforestry is repeated in this section but using population rather than area as the basis for assessing the extent of agroforestry. Figure 6 shows the global distribution of population in agricultural lands by tree cover. Our database counts 1.8 billion people living in agricultural lands. Of these, 746 million (41%) in 2000–2002 lived in landscapes with greater than 10% tree cover (tables 6 and 7). This is considerably higher than our previous estimate (Zomer et al., 2009), which reported 558 million (31%). This now drops to 150 million (8.3%) on land with greater than 30% tree cover and 45 million (2.5%) on land with greater than 50% tree cover. Table 6 shows that there are at least 100 million people living in landscapes with more than 10% tree cover in South Asia and Southeast Asia, with over 222 million in East Asia. This is a big increase from our previous estimate for East Asia (74 million). The estimate for Sub-Saharan Africa has decreased substantially, from 100 million to 67 million. The results are different from those based on area because of the variation in population density across the different regions. Agricultural populations are largest in South Asia and East Asia (together representing 60% of the global agricultural population) and both have significant agricultural areas characterized by both very high population densities.

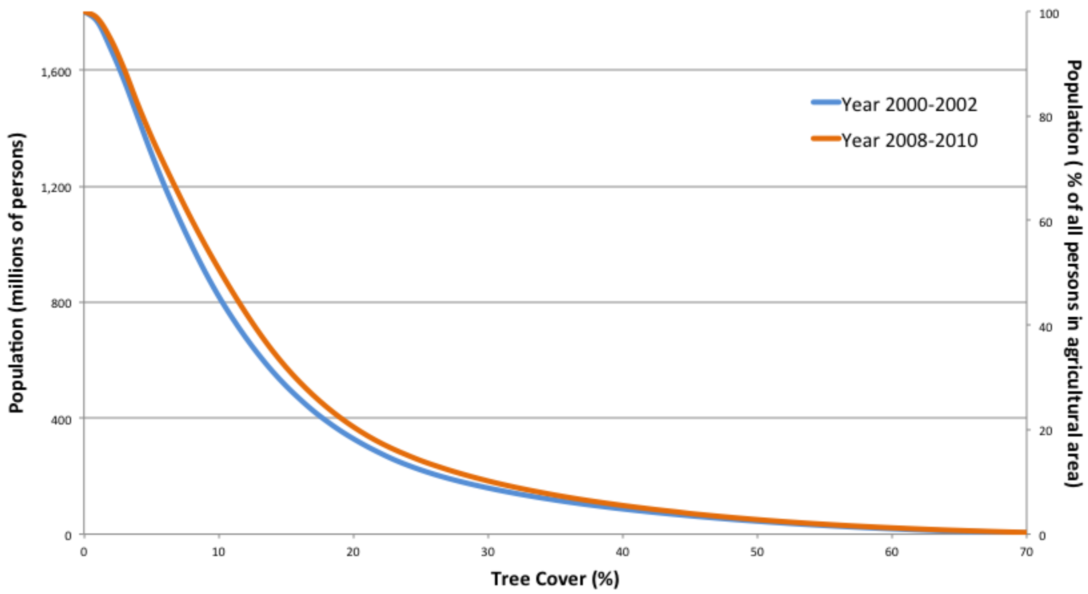


Figure 6. Global cumulative population in agricultural areas by tree canopy cover (left-hand Y axis absolute; right-hand Y axis relative numbers)

Table 6. Population (millions of people) living in landscapes with greater than 10%, 20%, 30% tree cover, using the averages of 2000–2002 and 2008–2010

Millions of persons	>10% tree cover		>20% tree cover		>30% tree cover	
Region/ period	**2000–2002**	**2008–2010**	**2000–-2002**	**2008–2010**	**2000–2002**	**2008–2010**
North America	18.1	18.2	12.1	12.8	7.6	8.3
Central America	14.2	14.8	10.5	12.2	6.9	8.3
South America	24.6	31.7	13.2	15.3	7.5	8.3
Europe	46.0	46.0	17.7	19.2	9.2	10.3
North Africa/Western Asia	13.5	13.8	4.9	3.8	1.7	2.0
Sub-Saharan Africa	67.6	70.1	28.2	28.8	13.0	12.1
Northern and Central Asia	8.6	6.8	2.1	2.1	0.8	0.9
South Asia	171.8	215.2	38.6	49.4	17.4	15.0
Southeast Asia	159.2	170.1	98.9	105.9	62.1	69.0
East Asia	222.0	249.6	75.7	90.3	22.8	37.4
Oceania	1.2	1.3	1.0	1.1	0.7	0.8
Global	**746.7**	**837.6**	**302.9**	**340.9**	**149.7**	**172.3**
Increment	90.9		38.0		22.6	

Table 7. Population (percentage of all people in agricultural areas) living in landscapes with greater than 10%, 20%, 30% tree cover, using the averages of 2000–2002 and 2008–2010

(% of all persons living in agricultural area)	>10% tree cover		>20% tree cover		>30% tree cover	
Region\period	**2000-–2002**	**2008-–2010**	**2000-–2002**	**2008-–2010**	**2000-–2002**	**2008–2010**
North America	65	66	44	46	27	30
Central America	91	95	68	78	44	54
South America	57	74	31	35	17	19
Europe	46	46	18	19	9	10
North Africa/Western Asia	13	13	5	4	2	2
Sub-Saharan Africa	37	39	16	16	7	7
Northern and Central Asia	28	23	7	7	3	3
South Asia	27	34	6	8	3	2
Southeast Asia	69	73	43	46	27	30
East Asia	50	57	17	21	5	8
Oceania	77	80	61	67	45	52
Global	**41**	**46**	**17**	**19**	**8**	**10**
Increment	5		2		2	

In terms of patterns observed across regions, the proportion of the agricultural population in agroforestry areas (where tree-canopy cover is >10%) is highest in Central America, Southeast Asia, Oceania (but with small population in total) and North America: each over 60%. But there are also significant proportions of rural populations living in agroforestry landscapes in South America, Sub-Saharan Africa and Europe.

There is a substantial increase in the number of people living in landscapes with greater than 10% tree cover, from 2000–2002 to 2008–2010 (Figure 6), from 746 million to 837 million (46% of all people living in agricultural areas). Southeast and East Asia see large increases of more than 10 million, with South Asia increasing by almost 45 million people (to 34% from 27%), and Sub-Saharan Africa increasing by nearly 3 million people (to 39%). North and Central Asia was the only region showing a decrease (from 8.6 to 6.8 million). South America increased by more than 7 million (from 57 to 74%).Thus, the extent of agroforestry, as measured either by area or population, remains shows signs of increase over time and is significant in absolute and relative (compared to overall extent in agriculture) terms. Further, this is not due to dominance by a few regions but rather because it is a common practice in many regions (Figure 7).

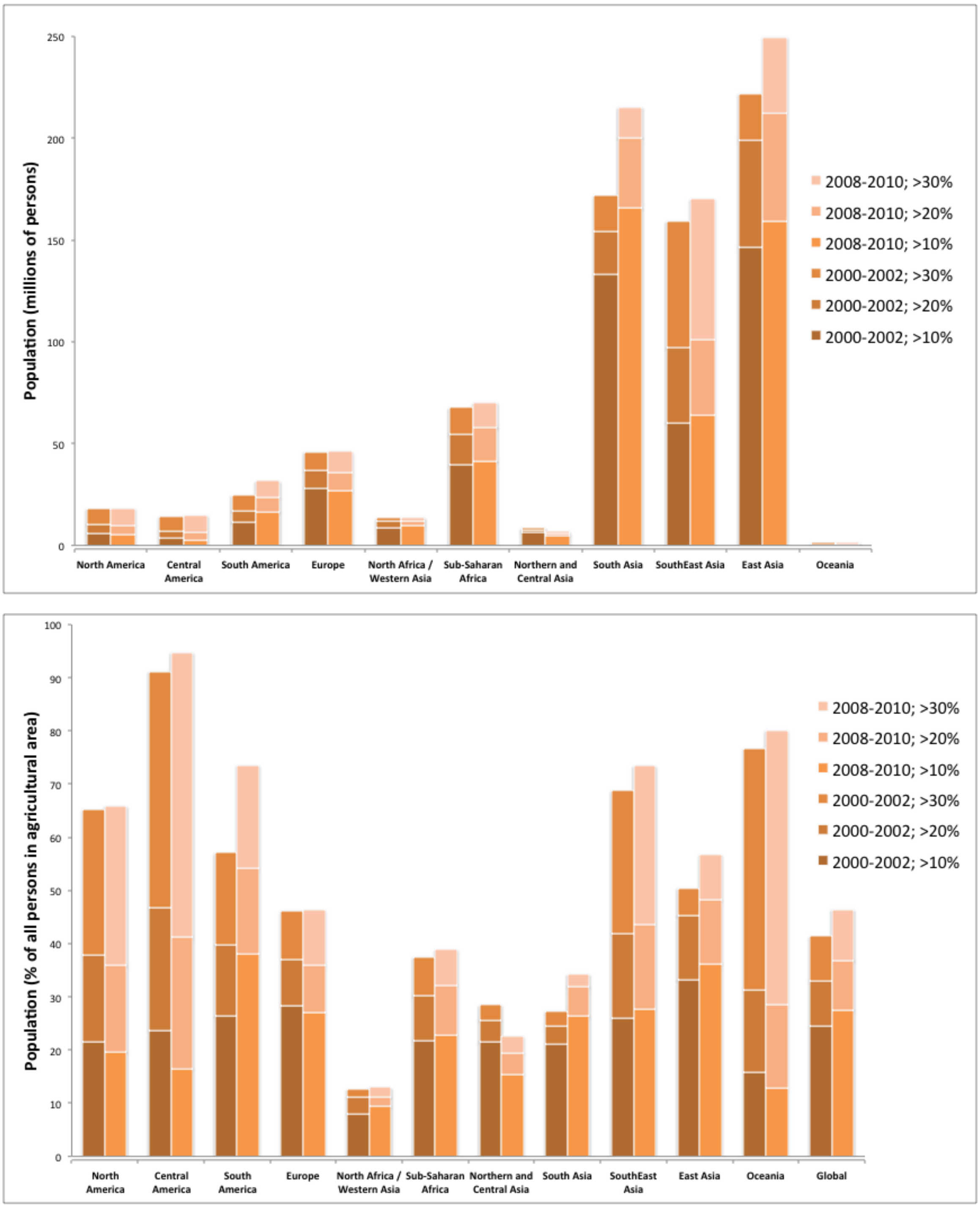


Figure 7. Population in agricultural areas by tree-canopy cover in different regions (upper panel: millions of persons; lower panel: percentage of population of agricultural areas)

The changes over the period from 2000 to 2010 described in this analysis of population and tree cover are changes in tree cover only. As explained above in regards to land cover, we have only used one population dataset from 2000, that is, the same used in the previous study by Zomer et al (2009). Thus, we can describe the changes in tree cover in relation to population and population density on land classified as agricultural in 2000 using the 2000 population dataset, meaning these are changes in tree cover and not changes in population.

There are likely to be additional changes due to increases or decrease in population during that time but these are not reflected here.

4.4 Agroforestry and population density

There are ‘obvious’ interactions of tree cover with population density, as discussed at length in Zomer et al (2009). An initial assumption can be made that there must be ‘less room’ for trees in densely populated areas that depend on agriculture. Indeed, throughout history, trees have been cleared to create space for agriculture. While agroforestry experience has shown this is not inevitable and there are other options, clearing forests for agricultural production is still a serious and widespread global issue. As before in our previous analysis, at the global level there is no obvious correlation between population density and tree density (Figure 8). Every tree cover/population density combination exists on agricultural land (that is, low/low, low/high, high/low, high, high). Central America continues to exhibit the overall highest tree cover across all population densities, which increases substantially from 2000–2002 to 2008–2010. Both South and East Asia have fairly high tree cover at lower population densities, however, both dipped to relatively low tree cover at densities above 100 persons per km^2. Most tree-cover/population density curves maintained relatively similar relationships between 2000–2002 and 2008–2010, with South America also showing substantial increases in tree cover at middle to higher population densities.

4.4 Estimates of the extent of agroforestry by aridity–wetness index

Tree cover has been shown to be strongly dependent on climate, as characterized by the Aridity–Wetness Index (Zomer et al 2009). There is wide variation across regions, with arid and semi-arid areas becoming disproportional in North Africa/West Asia, Sub-Saharan Africa, Northern and Central Asia, and South Asia. On the other hand, humid areas predominate in landscapes in Central America, Southeast Asia and South America. The average tree cover within agricultural land can be calculated as a function of the Aridity–Wetness Index (Figure 9) for different geographical areas, by normalizing the population distribution. These show similar trends for each region but with curves shifted vertically (that is, indicating different tree cover for a given aridity class), with Central America being highest and East Asia and South Asia lowest, with a difference between the two of about 15% tree cover for any given aridity class. There is a substantial drop in tree cover in Sub-Saharan Africa in the wetter, higher end of the curve between 2000–2002 and 2008–2010, which was already relatively low compared to the global average, whereas Southeast Asia has increased tree cover in these wetter classes. Central America has increased tree cover in all but the driest regions. Overall, global tree cover has mostly increased in the mid-ranges (approximately corresponding to semi-arid zones), with some decrease seen in the wettest regions.

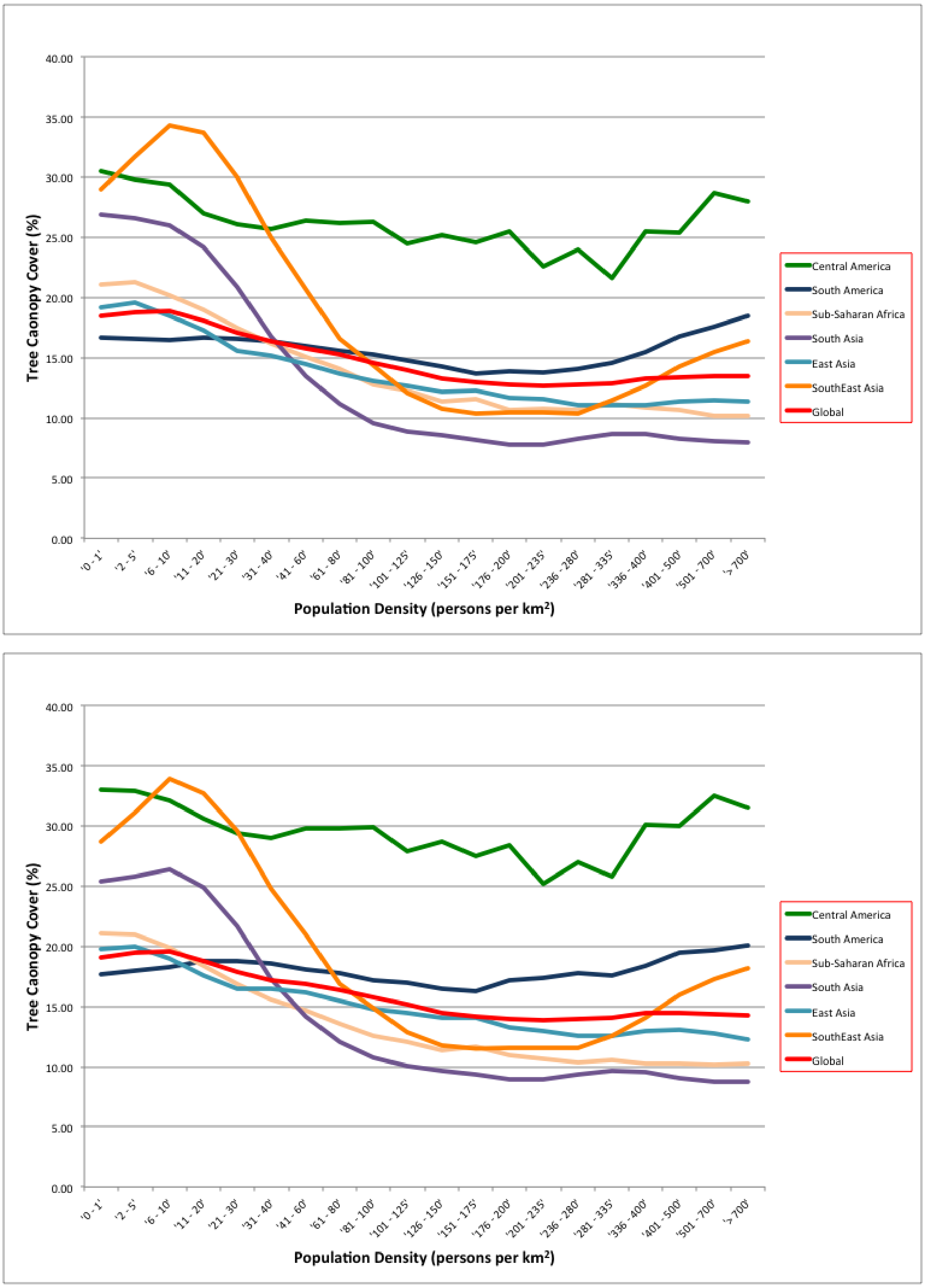


Figure 8. Tree-canopy cover on agricultural land by population density in seven regions of the world in two time periods (upper panel 2000–2002; lower panel 2008–2010)

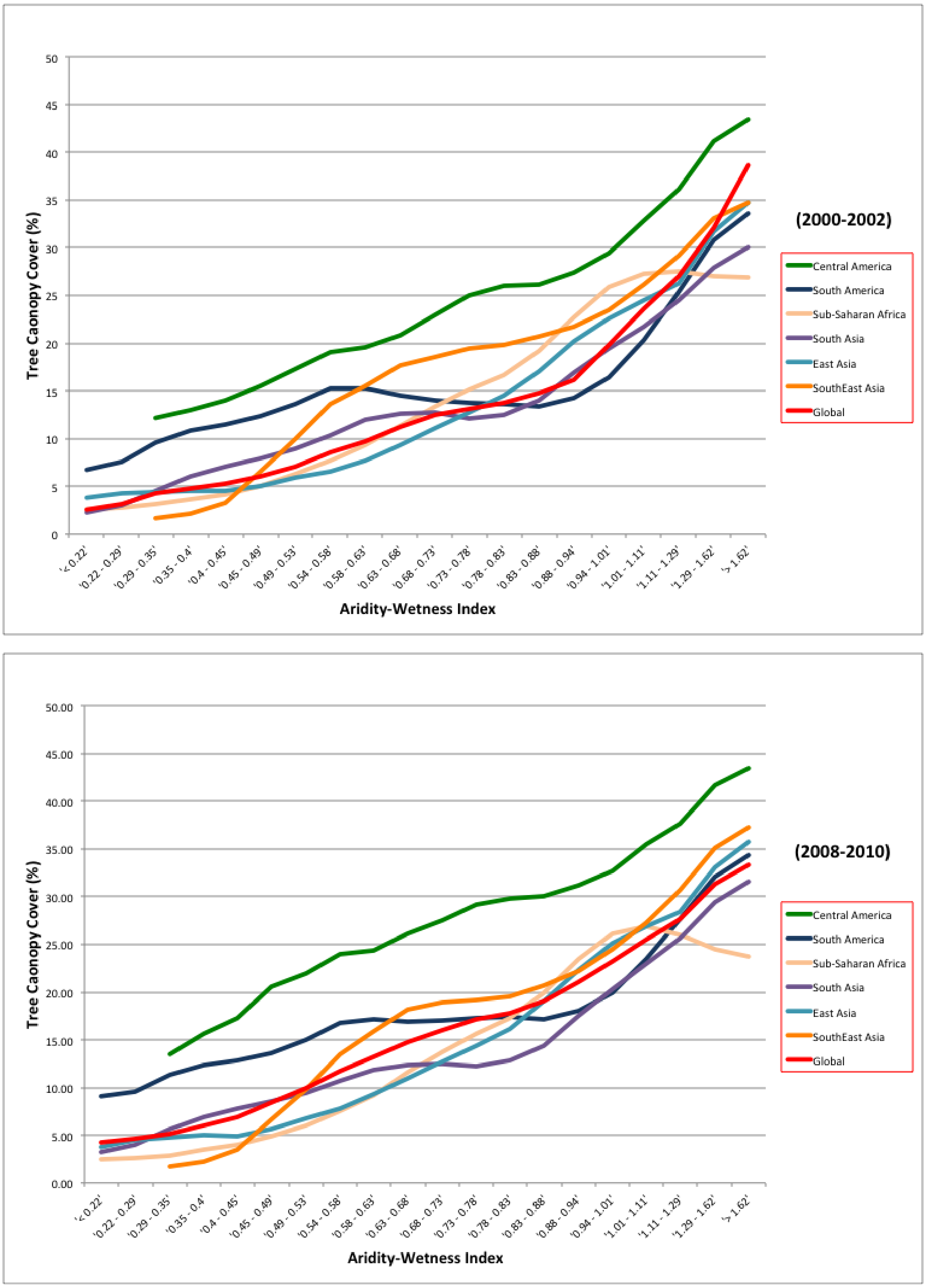


Figure 9. Tree-canopy cover of agricultural lands by Aridity–Wetness Index (higher values are wetter) for seven regions of the world (upper panel 2000–2002; lower panel 2008–2010)

5 Limitations

As discussed in Zomer et al (2009), we delineate below some important limitations and constraints associated with our analysis that should be kept in mind when using or reporting these results.

1) The data sets and methods used in this analysis have various limitations, peculiarities and ambiguities. These bound the interpretation of all the results and, hence, must be understood before using the results. The major limitations we have identified are listed below.
2) This is a global analysis. We are looking for global averages, trends and large-scale patterns. We cannot expect results for an individual pixel (1 km x 1 km) to be close to reality. But averages for large regions should be realistic, with trends and differences between regions reflecting real differences. For example, for each pixel classified as agriculture that actually has a large non- agricultural village in it, there is a pixel classified as urban or some other land use that has a substantial agricultural area.
3) Since the tree-cover variable is based on remote sensing, it is an estimate of percentage of crown cover not tree density *per se* nor of tree biomass. At landscape scale, the correlation between these is probably quite good within broad agroforestry systems and climate zones but this will not be true globally.
4) The interaction of a given percentage of crown cover with other agricultural activities varies with system, climate and other factors. For example, in the Sahel, 30% crown cover with mature parkland trees will enhance crop productivity relative to no trees; 30% crown cover of young trees will probably reduce crop production to close to zero (van Noordwijk and Ong 1999).
5) Agricultural land-cover classifications from remotely sensed data, particularly for Africa, are weak (Hannerz and Lotsch 2008). Many readers will be able to spot areas that are not included as agricultural but which, in their experience, have a large agricultural component. Much of the disagreement between land-cover maps arises from areas of low cropping density, where sparse agriculture tends to be confused with natural vegetation. For example, in Africa, where subsistence agriculture mixed with natural vegetation is a common practice, total agricultural area is quite underestimated. Therefore, our definition of agricultural areas may be biased towards more extensive (and productive) agricultural systems. On the other side, we should stress that in mosaics of agricultural area with natural vegetation, tree inclusion is more likely a natural presence and less 'of use' for human needs, as in agroforestry systems.
6) Our 'agricultural land' class does not include areas dominated by tree crops. Further, we are not able to include land classified as 'forest' but which we would call 'agroforest': forest which is managed more or less intensively by smallholders producing timber and non-timber products.
7) Discrepancies between the area we found as agricultural and other sources may be further compounded by the difference between *de facto* and *de jure* classifications.

8) The tree-cover data is also interpreted from remote-sensing data. MODIS VCF is likely to underestimate tree cover in general. Comparisons with ground tree-cover databases in southwestern USA (FIA and SWRrGAP), Utah, Arizona and Colorado, showed that VCF tree-canopy cover Collection 3 (the one used in the earlier analysis) had slightly positive or nil bias for low tree-canopy cover (0-10%), with bias becoming increasingly more negative (underestimates tree-canopy cover) as tree-canopy cover increases (White et al 2005). White et al reported in general a bias of -14/-18 % for southern USA, concluding that errors are unlikely to be related to habitat fragmentation or variation in canopy height but may be influenced by scaling discontinuities between ground and satellite resolutions. In concordance with this report, a previous study we did showed that while tree-canopy cover assessed from MODIS on agroforestry in India was about 8%, on-ground tree-canopy cover (assessed with high resolution imageries) was about 11% (Zomer et al 2007). Collection 3 is an average over the year 2000 and uses an algorithm that has been shown to need improvement. In fact, an assessment for 11 study areas in Africa (Rokhmatuloh et al 2005) showed an average prediction error of about 12% with VCF Collection 3. VCF Collection 5 improved this substantially but still likely has a relatively high average prediction error in excess of 6% (see sub-section on Geodatasets).
9) The population layer is a statistical interpolation built from a range of data sources and assumptions and from different levels of resolution in different regions. Population census, available for political regions, as districts or counties, is redistributed spatially based on night imageries of artificial light distribution. Such political boundaries for census data are wider for lower populated areas. However, bias exists in districts with high populations with small political boundaries where strong lighting might be produced from infrastructure. For instance, lights on highways can infer high populations yet few people live adjacent to highways.
10) We have no information on configuration of trees in the landscape. A 1 km x 1 km pixel classified as agricultural land and having 49% tree cover could be:
    a. 51% treeless cropland and 49% dense forest, with a hard boundary;
    b. 100% trees and crops fully integrated at the finest scale; or
    c. anything in between.
11) We have no information on the nature and level of interaction between the people in a pixel and the assumed agroforestry. A 1 km x 1 km pixel classified as agricultural land with 49% tree cover and 100 people could be:
    a. 100 people living in, and dependent on, an integrated agroforestry system;
    b. 51% treeless cropland with 100 agriculturalists living on it plus a people-less forest they are prohibited from entering; or
    c. 51% treeless cropland with one commercial farmer working on it and 99 people living in a forest village and working in a paper mill.
12) Readers knowledgeable about specific geographical areas will identify agricultural areas that are omitted from the land-cover data available. Many such areas will have been classified as woodlands or forests instead of agriculture. This means our

estimate of the extent of agroforestry is conservative: much, if not all, of the misclassified agricultural areas are likely to be under agroforestry.

13) In all interpretations and descriptions, we must remember that the analysis is based on cross-sectional data. The climate (and region) is assumed as a fixed conditioning variable or explanatory variable (economists' exogenous) (ignoring any hypotheses about changing tree cover changing local climate). But both population and tree cover are response variables (endogenous) and evolve through complex interactions with each other. It is tempting but not valid to explain tree cover by conditioning on population (for example, 'There are few trees here because there are a lot of people' or, vice versa, 'There are few people here because there are a lot/few trees'). However, it is useful to condition on one to detect patterns in the other. For example, if two agricultural areas with the same climate and population have very different tree cover there is something to understand and explain. Likewise, if there are two areas with the same climate and tree cover but very different populations.
14) It is important to note that areas of low tree cover and relatively high population do not mean that people are living without the benefits of trees. There may be nearby woodlands/forests or they may be purchasing tree products which are produced elsewhere.

6 Summary/conclusions

We believe the following key messages can be gleaned from this reanalysis and update of Zomer et al (2009).

6.1 Updated conclusions from previous analysis

1) Tree cover remains a common feature on agricultural land. It is, therefore, essential that this is recognized by all involved in agricultural production, planning and policy development.
2) Agroforestry, if defined by tree cover of greater than 10% on agricultural land, is widespread; found on more that 43% of all agricultural land area globally; and linked to 30% of rural populations. Based on our datasets, this represents over 1 billion hectares of land and more than 900 million people. Agroforestry is particularly prevalent in Southeast Asia, Central America and South America with over 50% of the agricultural areas under agroforestry.
3) It is not possible to describe the resulting patterns as ‘good’, ‘bad’, ‘appropriate’ or ‘inappropriate’ tree cover. We did not analyse the costs and benefits associated with these agroforestry lands nor the implications of a change in tree cover. However, the existence of extensive areas of agroforestry, even in arid areas, shows that such systems are viable in some sense.
4) There is a large variation in tree cover on agricultural land. From continental scale down to the smallest detectable in this analysis (1 km^2), there is variation in tree cover on agricultural land. But some major trends stand out.
5) There is a strong association between aridity and tree cover. The more humid the climate, the higher the level of tree cover. The results from Southeast Asia, Central America and South America are examples of this relationship. However, there are still many exceptions to this rule—high tree cover found in more arid zones and low tree cover found in more humid zones—that are explained by other factors.
6) There is no general trade-off in agricultural landscapes between people and trees. Within aridity classes and continents, there are distinct patterns in the relationship between trees and people but these do not generally correspond to either a negative or positive correlation except in the very low or high range of tree cover.
7) Large-scale, tree-cover patterns cannot be fully explained by aridity, population density or region. This points towards the importance of other factors like tenure, markets or other policies and institutions in affecting incentives for tree planting and management, as well as the historical trajectory that has lead to the current pattern.
8) Tree-cover patterns and relationships to other variables like aridity or population vary considerably across sub-continents. ‘Global’ results are rarely replicated in any specific subcontinent and hence may not be practically applied. Further investigations at finer regional scales are likely, therefore, to prove even more illuminating in terms of understanding where in the landscape agroforestry is practised.

6.2 Conclusions from the current time-series analysis

1) A comparison of the amount of agricultural land with tree cover in the year 2000 showed significant differences between the earlier analysis based on VCF-C3 and the current analysis using the updated VCF-C5. There are large reductions in estimates of tree cover on agricultural land particularly evident from West Africa, Tanzania, parts of Ethiopia, Brazil and Nepal. The new estimates of tree cover tend to be higher in China, northwestern India, parts of Argentina, and the eastern coast of Mexico. The percentage of land with greater than 10% tree cover globally is reduced from 46% of all agricultural land globally in the VCF-C3 to 40% in the VCF-C5, amounting to a reduction of more than 1.1 million km^2.
2) Globally, a (revised) cautious estimate of agricultural land that involves agroforestry for the year 2000 (that is, 2000–2002) is 13% (>30% tree cover), with a more realistic one being about 40% (>10% tree cover). Estimates for South American agriculture have been revised significantly downward from 81% to 53%, as have estimates for Sub-Saharan Africa (from 47 to 27%). Significant proportions of land under agroforestry are found in Europe (revised upward from 40% to 49%), North America (40%) and East Asia (revised upward from 23% to 45%), with all the remaining regions apart from North and West Africa (10%) and South Asia (19%) showing at least 27% of agricultural land under agroforestry. The percentage of agricultural land with substantial tree cover (>30%) continues to be remarkably high in some regions: over 47% in Central America and Southeast Asia.
3) Overall, the amount of tree cover on agricultural land globally increased substantially between 2000 and 2010, with the area with >10% increasing by more than 828 000 km^2 (from 40% to 43% of all agricultural land), >20% by more than 414 000 km^2 (from 21% to 23%) and >30 by more than 225 000 km^2 (from 13% to 14%). South America showed the largest increase in area with >10%—more than 489 000 km^2—an increase of 12.6% of all agricultural land. South Asia also showed a large increase (6.7%), along with East Asia (4.85%), Oceania (3.2%), Southeast Asia (2.7%) and North America (2%). Central America, which increased 1.6% to 96% of all agricultural land having greater than >10% tree cover showed a large increase in area with >20% (8.2%) and >30% (7.6%), indicating, perhaps, an increase in canopy density on agroforested land from maturing trees. Sub-Saharan Africa, which showed an increase of 1.85% of land with >10% tree cover, however, also showed a small decrease (- 0.6%) of land with >30%. Only Northern and Central Asia showed a decrease of agricultural land with >10% (- 2.9%).
4) Approximately 746 million people (41% of total population on agricultural land) lived in landscapes with greater than 10% tree cover in 2000–2002. This is considerably higher than our previous estimate (Zomer et al 2009), which reported 558 million (31%). This also is now reduced to 150 million (10%) on land with greater than 30% tree cover and 45 million (2%) on land with greater than 50% tree cover.
5) There are approximately 100 million people living in landscapes with more than 10% tree cover in each of the South Asia and Southeast Asia regions, with over 222 million in East Asia. This is a big increase from our previous estimate for East Asia (74

million). The estimate for Sub-Saharan Africa has decreased substantially, from 100 million to 67 million.

6) There is a large increase in the number of people living in landscapes with greater than 10% tree cover from 2000–2002 to 2008–2010, from 746 million to 837 million (46% of all people living in agricultural areas). Southeast Asia and East Asia show large increases of more than 10 million, with South Asia increasing by almost 45 million people (to 34% from 27%) and Sub-Saharan Africa increasing by nearly 3 million people (to 39%). North and Central Asia was the only region showing a decrease (from 8.6 to 6.8 million). South America increased by more than 7 million (from 57 to 74%).
7) Central America continued to exhibit the overall highest tree cover across all population densities, which increased substantially from 2000–2002 to 2008–2010. Both South Asia and East Asia have fairly high tree cover at lower population densities, however, both dipped to relatively low tree cover at densities above 100 persons per km^2. Most tree cover/population density curves maintained relatively similar relationships between 2000–2002 and 2008–2010, with South America also showing substantial increases in tree cover at middle to higher population densities.
8) There was a substantial drop in tree cover in Sub-Saharan Africa in the wetter, higher end of the curve between 2000–2002 and 2008–2010, which was already relatively low compared to the global average, whereas Southeast Asia increased tree cover in these wetter classes. Central America increased tree cover in all but the driest regions. Overall, global tree cover has mostly increased in the mid-ranges (approximately corresponding to semi-arid zones), with some decrease seen in the wettest regions.
9) The extent of agroforestry, as measured either by area or population, remains very significant in absolute and relative (compared to overall extent in agriculture) terms. Further, this is not due to dominance by certain regions but rather because it is a common practice in many regions.

Appendix

Appendix 1. Percentage of tree cover on agricultural land, showing the difference when using the years 2000 and 2010, compared to using the averages of 2000–2002 and 2008–2010

SubContinent	2000	2010	Difference 2010-2000	AVG 2000-2002	AVG 2008-2010	Difference Avg Years
North America	13.8	13.93	0.13	13.49	14.05	0.56
Central America	33.11	34.6	1.49	32.2	34.66	2.46
South America	17.68	19.9	2.22	17.33	19.01	1.68
Europe	14.24	14.5	0.26	13.65	14.07	0.42
North Africa/Western Asia	4.35	5.3	0.95	4.26	4.74	0.48
Sub-Saharan Africa	10.61	10.51	-0.1	10.75	10.52	-0.23
Nortern and Central Asia	10	7.92	-2.08	8.94	8.49	-0.45
South Asia	7.62	9.47	1.85	7.92	9.03	1.11
Southeast Asia	31.15	34	2.85	30.94	32.83	1.89
East Asia	13.25	14.98	1.73	12.6	13.96	1.36
Oceania	13.02	15.12	2.1	12.91	14.42	1.51
Globe	**13.99**	**14.82**	**0.83**	**13.68**	**14.43**	**0.75**

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